Small 3D Array Design Using Superdirective Antennas

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***Abstract*—In this paper, we present a compact broadside superdirective antenna array based on a planar parasitic superdirective unit-element. The array is designed for $905MHz$ frequency band, its dimensions are $200 \times 54 \times 24mm^3 (0.6\lambda \times 0.16\lambda \times 0.07\lambda)$, and it presents a directivity of $9.2dBi$ and radiation efficiency of 8.3%. Integrating the initial parasitic array in a PCB of $110 \times 70mm^2$, the array total dimensions are $200 \times 110 \times 70mm^3 (0.58\lambda \times 0.32\lambda \times 0.2\lambda)$, and it presents a directivity of $9.8dBi$ and radiation efficiency of 64%.**

Keywords*—*ESA, compact, end-fire, broadside, superdirectivity, parasitic element

I. Introduction

Electrically Small Antennas (ESAs) are very attractive for emerging multi-band wireless technologies. These antennas have narrow bandwidths, low efficiencies and quasi-omnidirectional radiation patterns. However, for some RF pointing devices, in addiction to compactness, high directivities are required. In such a case, superdirective ESAs, where the array elements are put very closely together, may be an acceptable solution.

Since the pioneer works of I. Uzkov [1] and of E. N. Gilbert and S. P. Morgan [2], an important research was done on superdirective arrays [3]-[9]. Early works were mainly about the design of wire-antenna arrays [3]-[4]. A three-element fully-driven monopole-based array was presented in [3]. O'Donnell and Yaghjian showed that, in wire-type arrays, the parasitic (shorted) array presents approximately the same directivity as the fully-driven one [4]. Furthermore, Yaghjian et al. showed that in this type of arrays not only superdirectivity is feasible but also supergain [5]. An important chapter summarizing early works on superdirective arrays is presented in [6]. Recently, multiple planar parasitic superdirective ESAs were presented [7]-[9]. In this paper, we propose using such arrays as unit-elements to design compact classical 3D broadside arrays. [1]

II. Simulations and Results

In [11] we presented a two-element parasitic superdirective array with an inter-element distance of 0.1λ and total dimensions of $54 \times 24mm^2$. It presents a simulated (HFSS [12]) maximum total directivity of $7dBi$ and radiation efficiency of 7.1%. The Half-Power Beamwidth (HPBW) in horizontal and vertical planes (XOY and YOZ) are respectively 110^o and 80^o and the Front to Back Ratio (FBR) is equal to $9dB$. Two elements of this array are stacked with an inter-element distance of $200mm (0.6\lambda)$ to design a 3D broadside array. Fig. 1(a) shows the array geometry and dimensions in mm, where elements 1 and 3 are excited with equal power, while elements 2 and 4 are loaded with a capacitor of $5.1pF$ (refer to [11] for more details on the loads calculation method). The antenna simulated 3D total directivity radiation pattern given in Fig. 1(b) reveals a directive pattern with a maximum total directivity of $9.2dBi$ toward the broadside direction (Yo). The HPBW in horizontal and vertical planes are now respectively $110°$ and $45°$, FBR is $8.6dB$ and Side Lobe Level (SLL) is $-13dBi$. Furthermore, Fig. 1(c) shows that antenna's broadside total directivity $(D_{(\theta=90^o, \phi=270^o)})$ is maximal around the resonance frequency of $905MHz$ (since the two elements are identical we are only showing the reflection coefficient of one of them). Finally, the antenna presents a simulated radiation efficiency of 8.3%. Comparing with the initial end-fire array, it can be noticed that the total directivity is increased by $2.2dB$, the horizontal HPBW is the same, while the vertical one is divided by 1.8. As for antenna's FBR and radiation efficiency, they are approximately the same as the initial end-fire's ones.

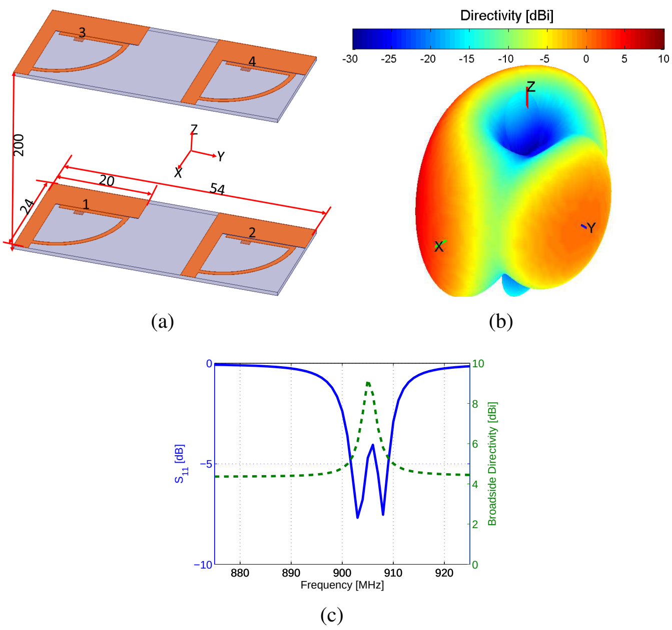

Fig. 1. Broadside array geometry and simulated parameters. (a) Geometry and dimensions, (b) 3D total directivity radiation pattern, and (c) input reflection coefficient magnitude and end-fire total directivity.

The initial end-fire array was integrated in a PCB with total dimensions of $110 \times 70mm^2$ and optimized for operating at

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$866MHz$ frequency band. The integration in the PCB was done via a study similar to the one presented in [14]. This antenna presents a superdirective pattern with a maximum total directivity of $7.2dBi$. The HPBW in horizontal and vertical planes are respectively $74°$ and $110°$, and the FBR is $8.4dB$. The antenna has a radiation efficiency of 62%. Again, two elements of this array are stacked with an inter-element distance of $200mm$ to form a 3D broadside array as shown in Fig. 2(a). Elements 2 and 4 are excited with equal power, while elements 1 and 3 are loaded with an inductor of $4.35nH$. As it can be seen from the antenna simulated 3D total directivity radiation pattern given in Fig. 2(b), the antenna is superdirective with a maximum total directivity of $9.8dBi$. The HPBW in horizontal and vertical planes are respectively $76°$ and $45°$, FBR is $8.4dB$ and SLL is $-10.6dBi$. Fig. 2(c) shows that antenna's broadside total directivity $(D_{(\theta=90^o,\phi=90^o)})$ is also maximal around the resonance frequency of $866MHz$. Finally, the antenna presents a simulated radiation efficiency of 64%. Comparing with the initial end-fire array, it can be noticed that the total directivity is increased by $2.6dB$. The horizontal HPBW is almost the same, while the vertical one is divided by 2.4. As for antenna's FBR and radiation efficiency, they are approximately the same as the initial end-fire's ones.

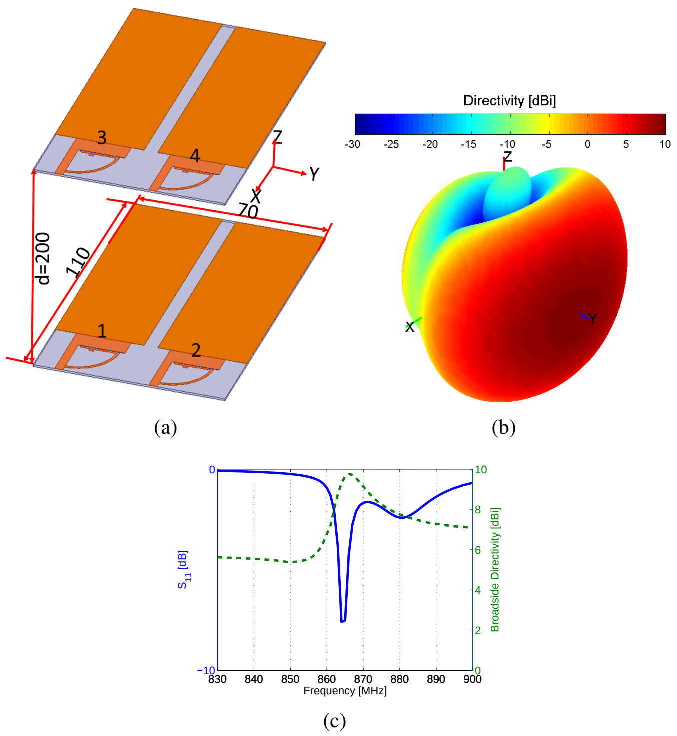


Fig. 2. Broadside array on a PCB geometry and simulated parameters. (a) Geometry and dimensions, (b) 3D total directivity radiation pattern, and (c) input reflection coefficient magnitude and end-fire total directivity.

III. Distance Effect

To study the effect of the distance (d) on the array performance, we vary this distance in the PCB integrated array from 0.01λ to λ while monitoring antenna's input reflection coefficient, total directivity and radiation efficiency. Fig. 3(a) shows the array simulated input reflection coefficient magnitude in dB as a function of the distance. The figure shows that for $d = 0.01\lambda$ the array resonance frequency is shifted to $969MHz$. This is due to the high mutual coupling that appears as a decrease in the array electrical length. As the distance increases the array resonance frequency decreases to converge to the one of the unit-elements. Fig. 3(b) shows the array simulated maximum total directivity and radiation efficiency as a function of the distance. The figure shows that for very small distances, the antenna's efficiency is maximal and as the distance increases the efficiency decreases. This is mainly due to the the lost of superdirectivity for very small distances (superdirectivity is achieved by current opposition on the two elements which reduces the antenna efficiency). Fig. 4 shows the array simulated 2D total directivity radiation patterns at the design frequency $(866MHz)$ as a function of the distance. The figure shows that for very small distances, the array directive pattern is lost and the array has a quasi-omnidirectional radiation pattern. This is also due to the high coupling effect that makes the applied loads unsuitable for having directive unit-elements. As the distance increases, the achieved directivity increases till 0.8λ when it starts decreasing again. Furthermore, as expected, for distances greater than 0.5λ side lobes appear in the vertical plane and as the distance increases SLL also increases.

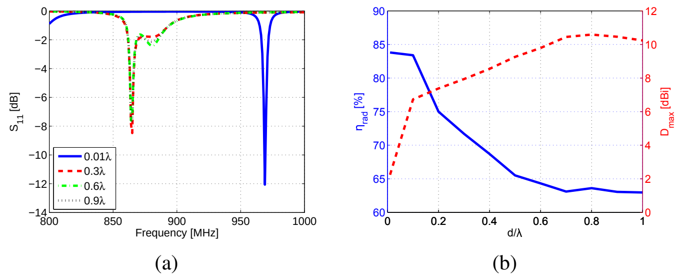


Fig. 3. Broadside array on a PCB simulated parameters as a function of the distance. (a) input reflection coefficient magnitude, and (b) maximum total directivity and radiation efficiency.

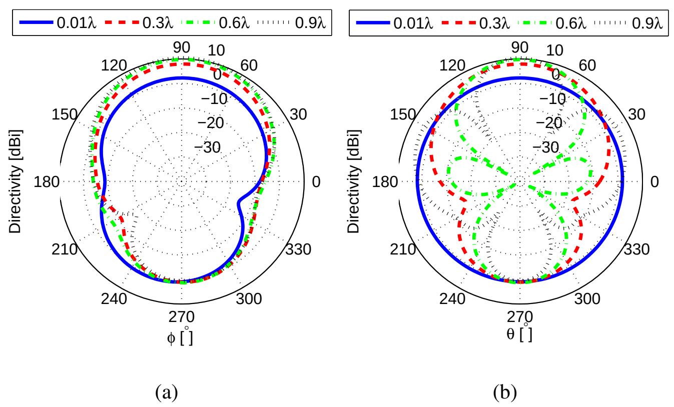


Fig. 4. Broadside array on a PCB simulated 2D total directivity radiation patterns as a function of the distance. (a) Horizontal plane and (b) vertical plane.

IV. Results Validation via Measurements

In [13], it was shown that the measured parameters of the end-fire array on a PCB are in a good agreement with the simulated ones. Fig. 5(a) shows a photograph of the fabricated prototype of the broadside array on a PCB and Fig. 5(b) shows its measured input reflection coefficient magnitude. The measured resonance frequency is $896MHz$ (a frequency shift of 3.5%). This shift is probably due to the UFL cable effect, the dispersion of the commercial SMD loads, and the modifications in the antenna geometry for fixing the two elements together. The higher losses in measurements can be attributed to the losses in the UFL cable and the SMA connections. The measured radiation efficiency in a reverberation chamber [15] is about 60.5% (Fig. 5(c)). The antenna far-field radiation pattern was measured in SATIMO stargate (SG 32) near-field measurement system. The measured 3D and 2D total directivity radiation patterns at the resonance frequency are given in Fig. 5(d) and Fig. 6. The measured pattern in the main-beam direction is in acceptable agreement with the simulated one. A considerable divergence is noticed in the backward direction. This divergence may be due to the feeding system, and the measuring system and environment. The measured directivity is about $8.6dBi$ and the HPBW in horizontal and vertical planes are respectively $56°$ and $84°$.

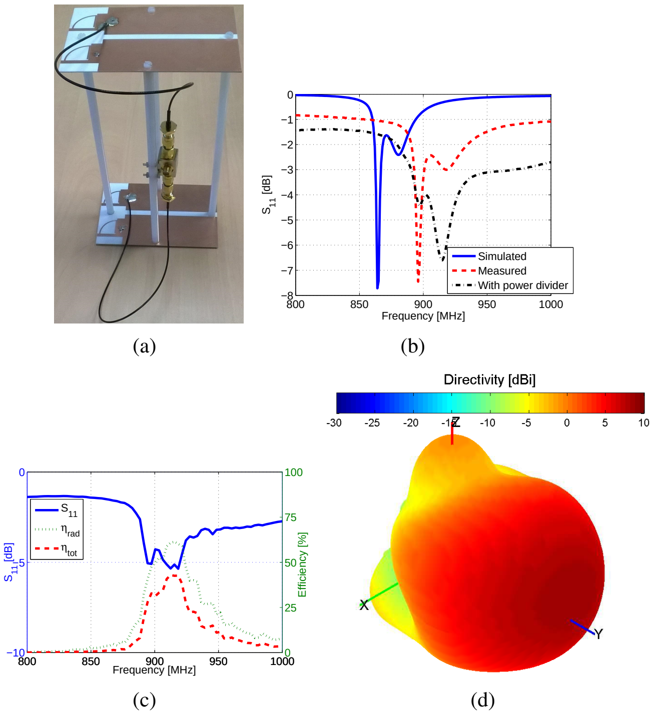
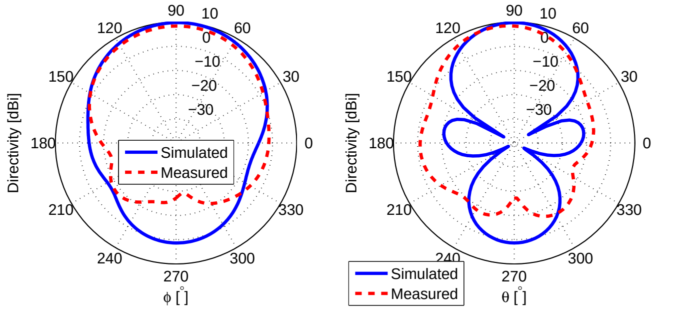


Fig. 5. Broadside array on a PCB prototype and measured parameters. (a) Fabricated prototype, (b) input reflection coefficient magnitude, (c) efficiency and (d) 3D total directivity radiation pattern.

V. Conclusion

In this paper, we presented a compact broadside array based on a planar parasitic superdirective unit-element. The array dimensions were $0.6\lambda \times 0.16\lambda \times 0.07\lambda$, and it presented a total directivity of $9.2dBi$. Integrating the unit-elements in a PCB of $110 \times 70mm^2$, the array dimensions were $0.58\lambda \times 0.32\lambda \times 0.2\lambda$, and it presented a total directivity of $9.8dBi$ and radiation efficiency of 64%. By using a 2×2 superdirective elements, a broadside array of $0.58\lambda \times 0.58\lambda \times 0.2\lambda$ presenting a total directivity of $11.4dBi$ and radiation efficiency of 72.3% can be achieved.



(a) (b)

Fig. 6. Broadside array on a PCB measure 2D total directivity radiation patterns. (a) Horizontal plane and (b) vertical plane.

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